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INFORMAL REPORT

TMI-2 CORE DEBRIS BED COOLABILITY

P. Kuan

EG&G Idaho

Work performed under
DOE Contract
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1. INTRODUCTION

The loss-of-coolant accident on March 28, 1979 at the Three Mile Island, Unit 2 (TMI-2) reactor caused severe fuel damage and core disruption. In 1984 and 1985, in-core camera and acoustic examinations of the reactor were performed. These examinations found: (a) a cavity in the upper part of the core, bounded on the periphery by partially damaged fuel assemblies; (b) a rubble bed of shattered fuel and oxidized cladding below the cavity; and (c) shattered particles together with lumps of material, apparently solidified from a molten state, in the lower plenum. Probing with a pointed tool indicated that the upper rubble bed terminates at a solid crust about a meter below its top surface. The term, debris bed, as used here, refers to both the rubble and the solid bed underneath it. The condition of the region between the bottom of the rubble bed and the lower plenum is unknown, since this area, consisting of the lower core and the core support structures, has not been explored. Figure 1 shows the known core configuration.

Scenarios of the TMI-2 accident, constructed to explain the present core configuration, generally agree on what happened during the early phase of the accident. Coolant was lost through a failed pressurizer power operated relief valve, and the core was uncovered. The upper central region of the core heated to about 1100 K from its own decay heat. Some fuel rods could have ballooned and ruptured at this time. Examining some of the still-recognizable fuel rods in the peripheral assemblies may provide evidence for this ballooning and rupturing. At temperatures above 1100 K, steam oxidized the fuel-rod zircaloy cladding to produce an additional heat source. Once temperatures exceeded 1600 K, the oxidation became so rapid that the upper parts of fuel rods reached temperatures above the melting point of zircaloy (about 2100 K) within a few minutes. Melted zircaloy, capable of liquefying some fuel, could have flowed down the fuel rods and congealed where the hard crust was found below the present rubble bed.

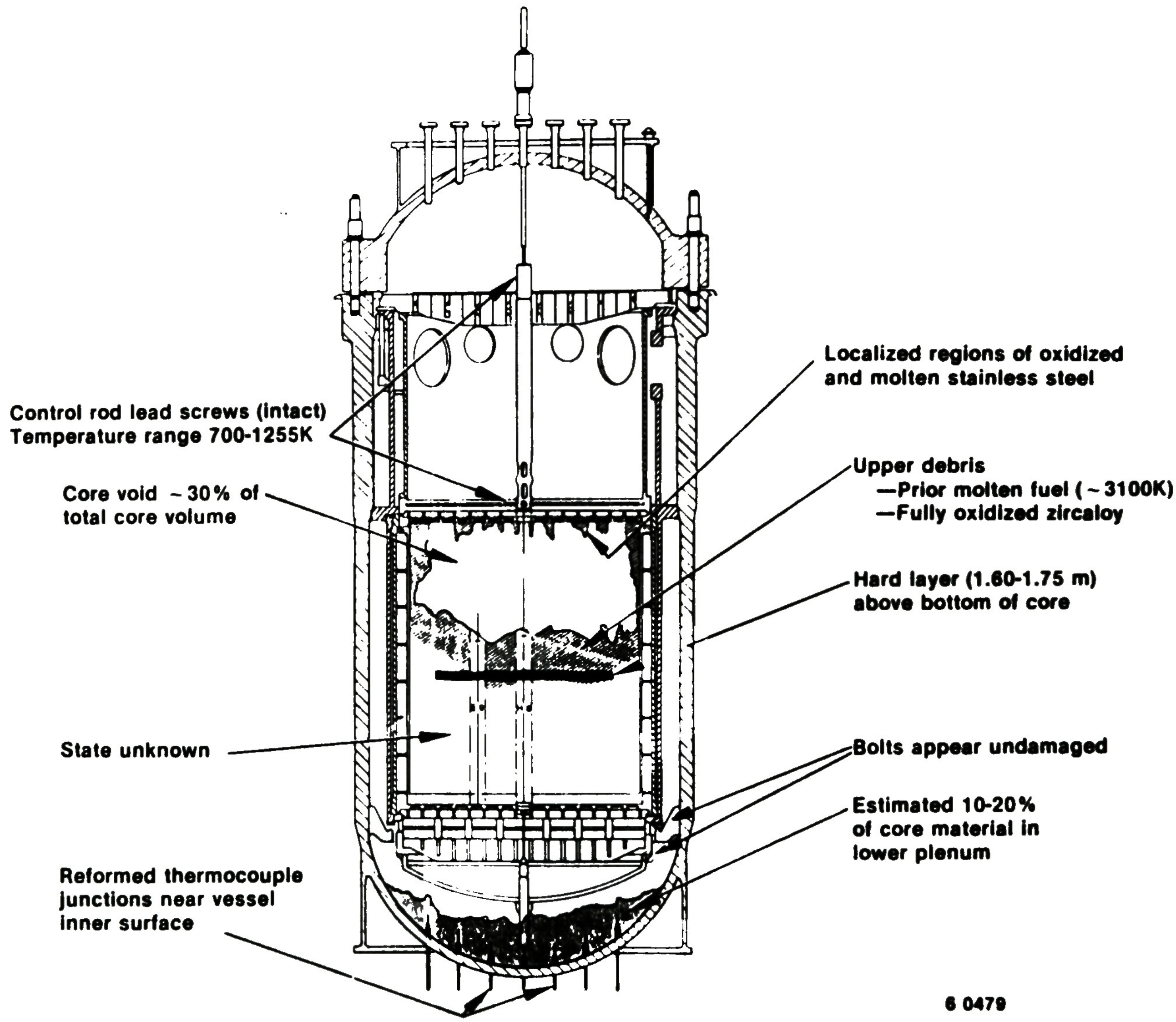

Figure 1. Known TMI-2 reactor-vessel and core conditions.

Accident scenarios beyond this phase of zircaloy melting and fuel liquefaction are more speculative. Some 2 h, 54 min into the accident, one of the reactor coolant pumps was turned on momentarily. Estimates show as much as 30 m^3 of cooling water could have been pumped through the reactor core at this time. By then, much of the fuel cladding in the upper core would have oxidized and become very brittle. The cooling water could have shattered the brittle cladding and the fuel pellets thus forming the observed rubble bed. Half an hour later, emergency core cooling water was introduced to the reactor cooling system by the safety injection system.

About 20 min after this emergency core cooling water flooded the core (3 h, 46 min into the accident), several events indicated that there was another major core-configuration change. The count rate of a source-range neutron detector located on the outside of the reactor increased sharply; many of the in-core self-powered neutron detectors (SPNDs) located near the bottom of the core alarmed; and a pressure pulse of about 2 MPa was observed. One hypothesis is that these events signified the relocation of core material into the lower plenum. Neutron streaming from the relocated fuel through the lower vessel head would explain the source-range count rate increase; passage of hot, liquid core material from above may have caused the SPNDs in the lower core to alarm; and steam, rapidly formed from the interaction between hot core material and the coolant, undoubtedly resulted in the pressure pulse.

After these events at 3 h, 46 min, sustained emergency cooling water was delivered to the primary cooling system. Although no further sudden, drastic changes in the system's physical parameters were observed, the system did not completely stabilize until 16 h into the accident when a reactor coolant pump was again successfully started. References 1 through 3 present a more detailed discussion of the accident progression.

Core material relocation to the lower plenum raises questions about the TMI-2 accident progression. Among these are:

- What was the core configuration before the relocation?

  Defueling the TMI-2 reactor, determining what remains of the core geometry, and studying the mass distribution below the rubble bed and the hard crust may help answer this question. Until then, we can only conjecture that a solid region existed below the rubble bed. Relocated zircaloy, liquefied fuel, and possibly the silver-indium-cadmium control material formed this solid region.

- How could this solid region of relocated zircaloy and liquefied fuel have failed and allowed core material to relocate in the lower plenum?

  One suggestion is that the mass of solid core material below the rubble bed was not coolable; it melted and flowed down to the lower plenum, presumably about 3 h, 46 min into the accident. If this is so, there is still a problem explaining the time of the relocation.

This report studies the thermal behavior of debris beds impermeable to cooling water. It considers these debris beds as idealizations of the slumped TMI-2 core as conjectured between 2 h, 54 min and 3 h, 46 min into the accident. Section 2 calculates the decay heat levels as functions of time after shutdown, assuming various fractions of the more volatile fission products were released during the earlier high temperature transient up to 2 h, 54 min. Section 3 determines the thermal properties of the debris-bed material as functions of fuel content in a mixture of uranium dioxide and zircaloy. With these parameters, Section 4 calculates the equilibrium temperature profiles in slab geometry for various sizes and compositions of the debris bed. Calculations were carried out to determine the minimum thicknesses of debris beds that have a molten interior under equilibrium conditions and the equilibrium thicknesses of the solid crusts of debris beds having molten interiors as functions of their overall dimension. Hopefully, these calculated parameters will help determine a lower size limit of the TMI-2 debris bed below which molten core material could not have flowed down to the lower plenum. In Section 5, a one-dimensional, slab geometry, transient heatup calculation was performed for a best-estimate configuration of the TMI-2 debris bed after its formation (about 2 h, 54 min into the accident). The amount of molten material calculated to be inside the debris bed at about 3 h, 46 min into the accident can be compared to the amount of core material found in the lower plenum. Finally, Section 6 summarizes the results and discusses their uncertainties and limitations.

2. DECAY HEAT LEVELS

The TMI-2 core contained 82,000 kg of uranium, enriched to an average of 2.54% in U-235. The reactor had acquired an average burnup of 3250 MWD/MTU from operation for over 3 mo before the accident in 1979.[4] This study assumes the reactor operated continuously near full power at 2670 MW for 100 days. These simplifying assumptions--average core enrichment and operating history--were the basis for the ORIGEN2 code[5] calculation of decay heat from the entire core during the first 24 h after reactor scram. The results obtained here show a discrepancy of about 5% when compared to the isotopic inventory calculated for the time immediately after the scram using a more detailed model (see Reference 4).

Reference 6 shows that fuel rods heated to above 2000 K, such as in the TMI-2 accident, are expected to release a significant fraction of the more volatile fission products. These more volatile fission products, such as krypton, xenon, iodine, cesium, and tellurium, contribute a significant fraction of the decay heat. Decay power in the fuel is reduced accordingly as these fission products are released from the fuel. The release fractions of these fission products from the TMI-2 core, especially in the debris region, have not been determined. This study assumes that these fission products were released in equal fractions and uses their release fraction as a free parameter when determining decay heat as a function of time after reactor scram. During the first day after reactor scram, these fission products contributed between 17 and 30% of the total core decay power; the higher percentage corresponds to the time soon after scram.

Table 1 shows the power from the decay heat in the TMI-2 core as a function of time after reactor scram and also as a function of the release fraction of the above-mentioned volatile fission products. The values listed in the table were used in the following thermal analysis to compute the power densities of the debris beds.

TABLE 1. TMI-2 REACTOR CORE DECAY HEAT POWER (MW)

Time (h)	Volatile Fission Product Release Fraction					
	0.0	0.1	0.3	0.5	0.9	1.0
1	36.1	35.0	32.9	30.8	26.5	25.4
2	28.2	27.4	25.8	24.2	21.0	20.2
3	24.5	23.9	22.6	21.4	18.9	18.3
4	22.3	21.8	20.7	19.6	17.4	16.9
5	20.7	20.2	19.2	18.2	16.3	15.8
10	16.7	16.3	15.6	14.8	13.4	13.0
24	12.5	12.3	11.9	11.4	10.6	10.4

3. ONE-DIMENSIONAL DEBRIS BED THERMAL PROPERTIES

The following analysis considers only the uranium dioxide and zircaloy in the TMI-2 core. The core contained about 93,100 kg of uranium dioxide and 23,000 kg of zircaloy; most of the zircaloy was used as fuel rod cladding. The other materials in the core, such as alloys of steel, silver-indium-cadmium, and boron carbide-aluminum oxide, were not considered in the analysis because they comprised only a small fraction of the core mass inventory. Oxidized zircaloy (zirconium dioxide) was assumed to have the same thermal conductivity and specific heat as uranium dioxide (see Table 2). For this study, the constant values given in the table were used; Reference 7 contains material properties as functions of temperature.

The most likely scenario for forming a cohesive debris bed during a severe fuel damage accident is as follows: the zircaloy cladding melts, liquefies some of the fuel, flows downwards, and solidifies between the intact fuel rods in the lower core where the temperature is still comparatively low. The solidified cladding blocks the core and is a receptacle for subsequently relocated cladding and fuel. Before melting completely, this debris bed can be quite heterogeneous. The relocated material can vary from almost pure metallic zircaloy to a U-Zr-O ceramic. Also some fuel rods embedded in the solid matrix may have oxidized cladding; others may not. The debris bed could cover much of the core and be relatively thin. In such a scenario, a one-dimensional thermal conduction calculation, using the vertical coordinate as a spatial variable, should characterize fairly well the dominant, vertical temperature variation in the debris bed. In this type of calculation, the thermal properties of the debris bed have to be averaged in the horizontal plane.

Thus, the thermal conductivity of the debris bed is taken to be the volume-weighted average of the thermal conductivities of uranium dioxide and zircaloy, and is given by

$$k = \frac{\frac{f}{\rho(UO_2)}\,k(UO_2) + \frac{1-f}{\rho(zry)}\,k(zry)}{\frac{f}{\rho(UO_2)} + \frac{1-f}{\rho(zry)}} \qquad (1)$$

TABLE 2. THERMAL PARAMETERS USED IN DEBRIS BED THERMAL ANALYSIS

	Thermal Conductivity (W/m-K)		Density (kg/m^3)		Specific Heat (J/kg-K)	Heat of Fusion (J/kg)
	Solid	Liquid	Solid	Liquid		
Uranium Dioxide	2.5	11.0	10,000	8,000	500	274,000
Zircaloy	58.0	36.0	6,300	6,200	500	225,000
Zirconium Dioxide	2.5	11.0	5,800	5,800	500	706,000

where

k	=	thermal conductivity of debris bed
$\rho(UO_2)$	=	density of uranium dioxide
f	=	mass fraction of uranium dioxide
$k(UO_2)$	=	thermal conductivity of uranium dioxide
$\rho(zry)$	=	density of zircaloy
$k(zry)$	=	thermal conductivity of zircaloy.

Steady-state calculations made with the above volume-averaged thermal conductivity would give the exact temperature distribution and heat flux under the following conditions: First, the debris bed would consist of similar distributions of unreacted uranium dioxide and zircaloy in every horizontal plane; and second, the temperature in such a bed would not vary in a horizontal plane. However, the volume-weighted average cannot be applied with confidence to debris beds homogenized by melting. Because thermal conductivities in such a homogenized debris bed may not be related in any obvious way to the conductivities of their individual constituents, the equation's validity must be verified by experiments.

The mass-weighted average is usually the proper average for the specific heat and the heat of fusion. The averages are correct provided there is no chemical interaction between the zircaloy and the uranium dioxide, and a unique melting point can be defined.

Power density is another parameter in the thermal calculations. Since the decay heat is associated with the fuel, the power per unit volume depends on the fuel content in the volume. Assuming the total decay heat in the core is evenly distributed in the fuel, the power density in the debris bed is given by

$$P = f \cdot \rho \cdot P_0/M_0 \tag{2}$$

where

P = power density of debris bed

f = mass fraction of uranium dioxide

ρ = density of debris bed

P_0 = total core decay power

M_0 = total mass of uranium dioxide in core.

The density in the debris bed, ρ, is given by

$$\rho = \frac{1}{\frac{f}{\rho(UO_2)} + \frac{1-f}{\rho(zry)}} \tag{2a}$$

where

f = mass fraction of uranium dioxide

$\rho(UO_2)$ = density of uranium dioxide

$\rho(zry)$ = density of zircaloy.

4. EQUILIBRIUM TEMPERATURE PROFILES IN SLAB GEOMETRY

The time-independent, one-dimensional thermal conduction equation for slab geometry is

$$k\frac{d^2T}{dz^2} = - P \tag{3}$$

where

k = thermal conductivity (considered constant)

T = temperature

z = spatial variable

P = volumetric heat generation rate, or power density (considered constant).

For a slab of thickness, d, and with symmetric temperature boundary conditions at z = 0 and z = d, as shown in Figure 2, the solution of Equation 3 is

$$T(z) = T_0 + \frac{P}{2k} z(d-z) \tag{4}$$

where T_0 is the temperature at the surfaces.

Substituting the expressions for the debris bed conductivity, k, and the power density, P, as given by Equations 1 and 2 respectively in Section 3, the temperature distribution can be written as

$$T(z) = T_0 + \frac{f}{\frac{f}{\rho(UO_2)} k(UO_2) + \frac{1-f}{\rho(zry)} k(zry)} \cdot \frac{P_0}{2M_0} \cdot z(d-z) \tag{5}$$

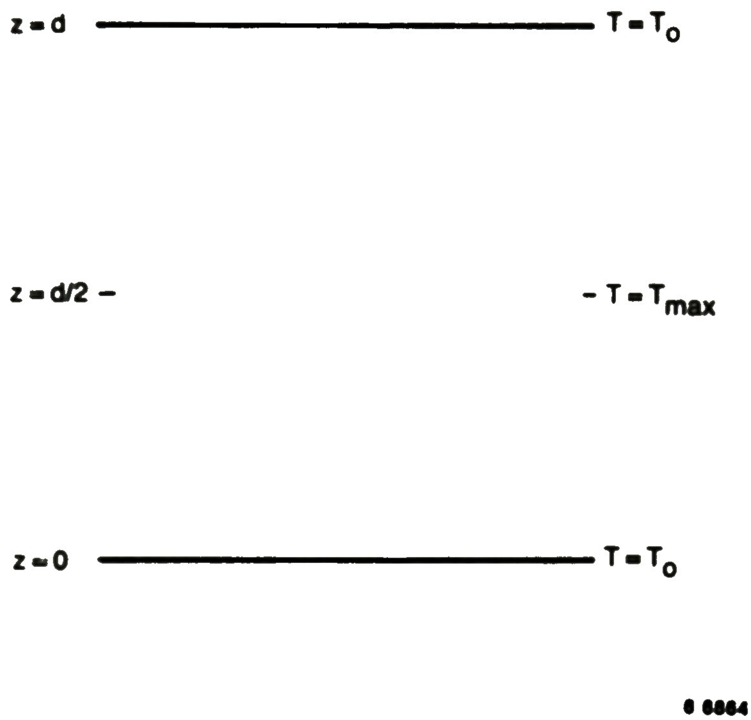

Figure 2. One-dimensional thermal conduction in slab geometry.

where

f	=	uranium dioxide mass fraction in debris mixture
$\rho(UO_2)$	=	density of uranium dioxide
$k(UO_2)$	=	thermal conductivity of uranium dioxide
$\rho(zry)$	=	density of zircaloy
$k(zry)$	=	thermal conductivity of zircaloy
P_o	=	total core decay power
M_o	=	total core uranium dioxide mass.

4.1 Minimum Thickness of Debris Beds with Molten Interior

In a melt-relocation scenario, the interior of the debris bed melts from its own decay heat. The molten front propagates outward until the solid crust becomes so thin it can no longer hold the molten material. This section computes the minimum thickness of such a debris bed. These computations use various release fractions of the more volatile fission products and fuel content of the debris bed and assume the debris bed has reached thermal equilibrium for a given power density.

For a debris bed of thickness, d, with symmetric temperature boundary conditions, as shown in Figure 2, the maximum temperature occurs at z equal to d/2. Equation 5 gives the maximum temperature as

$$T_{max} = T_o + \frac{f}{\frac{f}{\rho(UO_2)}\,k(UO_2) + \frac{1-f}{\rho(zry)}\,k(zry)} \cdot \frac{P_o}{8M_o} \cdot d^2 \qquad (6)$$

Substituting the numerical values of the k's and ρ's for solid mixtures given in Section 3, the maximum temperature is given by

$$T_{max} = T_o + \frac{100\ f}{7.37 - 7.17\ f} \cdot \frac{P_o}{M_o} \cdot d^2 \tag{7}$$

where P_o is in W, M_o in kg, d in m, T_{max} and T_o in K.

A debris bed composed mostly of U-Zr-O ceramic has a melting point of about 2700 K. The surface temperature will be about 600 K if the debris bed surfaces are in nucleate boiling under water at an approximate pressure of 7 MPa (1000 psia, saturation temperature about 560 K). If T_{max} is 2700 K and T_o 600 K, the debris bed thickness, d, in m, is given by

$$d = \sqrt{\frac{21\ (7.37 - 7.17\ f)\ M_o}{fP_o}} \tag{8}$$

where, again, f is the mass fraction of uranium dioxide in the mixture, P_o the decay power in W, and M_o the mass of uranium dioxide in kg having the decay power P_o. The interior of such a debris bed will be just on the verge of melting. Therefore, d is the minimum thickness of a mostly U-Zr-O ceramic debris bed with a molten interior.

Equation 8 is used to compute the minimum thickness of debris beds for various release fractions of the more volatile fission products. The calculation also considers fuel content and the time after shutdown, based on the decay power given in Table 1. The mass of uranium dioxide, M_o, corresponding to the decay power is 93,100 kg. Tables 3 through 5 give the results.

As seen from the tables, the minimum thickness of a debris bed with a molten interior is more sensitive to the debris fuel content than to the release fraction of the more volatile fission products, even though the latter is quite significant. The thermal conductivity increases while the power density decreases with the fuel content. Both factors increase the

TABLE 3. MINIMUM THICKNESS OF DEBRIS BED, IN METERS, WITH MOLTEN INTERIOR FOR VOLATILE FISSION PRODUCT RELEASE FRACTION EQUAL TO 0.1

Time	Fuel Mass Fraction, f			
(h)	0.3	0.5	0.9	1.0
1	0.99	0.65	0.24	0.11
2	1.11	0.73	0.27	0.12
3	1.19	0.79	0.29	0.13
4	1.25	0.82	0.30	0.13
5	1.30	0.86	0.31	0.14
10	1.44	0.95	0.35	0.15
24	1.66	1.10	0.40	0.18

TABLE 4. MINIMUM THICKNESS OF DEBRIS BED, IN METERS, WITH MOLTEN INTERIOR FOR VOLATILE FISSION PRODUCT RELEASE FRACTION EQUAL TO 0.5

Time	Fuel Mass Fraction, f			
(h)	0.3	0.5	0.9	1.0
1	1.05	0.69	0.25	0.11
2	1.19	0.78	0.29	0.13
3	1.26	0.83	0.31	0.14
4	1.32	0.87	0.32	0.14
5	1.37	0.90	0.33	0.15
10	1.52	1.00	0.37	0.16
24	1.73	1.14	0.42	0.19

TABLE 5. MINIMUM THICKNESS OF DEBRIS BED, IN METERS, WITH MOLTEN INTERIOR FOR VOLATILE FISSION PRODUCT RELEASE FRACTION EQUAL TO 0.9

Time	Fuel Mass Fraction, f			
(h)	0.3	0.5	0.9	1.0
1	1.13	0.75	0.27	0.12
2	1.27	0.84	0.31	0.14
3	1.34	0.88	0.32	0.14
4	1.40	0.92	0.34	0.15
5	1.44	0.95	0.35	0.15
10	1.59	1.05	0.39	0.17
24	1.79	1.18	0.43	0.19

minimum thickness. During the first day after shutdown, a debris bed with a molten interior could have a minimum equilibrium thickness as low as 0.1 m with 100% fuel and over 1.0 m with 30% fuel content.

4.2 Equilibrium Crust Thickness of Debris Beds with Molten Interior

The center of debris beds thicker than the minimum thickness, calculated in Section 4.1, will be molten under equilibrium conditions. Figure 3 shows a typical configuration of such debris beds.

The calculations performed here assume that heat transfer to the upper and lower surfaces of the debris bed is symmetric with respect to the mid-elevation of the debris bed. When the debris bed interior is molten to a certain extent, convection cells form in the molten region. Because the convections cells transfer more heat to the upper crust, the upper crust is generally thinner than the lower crust. Researchers at Fauske and Associates, Inc. are studying this effect.

Using the same nomenclature as before, the heat flux from the molten interior to either the upper or lower crust, assuming reflection symmetry about z equal to $d/2$, is given by $P(d-\Delta)/2$ under equilibrium conditions, where Δ is the thickness of the solid crust of the debris bed. With this boundary condition, the solution of the time-independent thermal conduction equation (Equation 3) is given by

$$\Delta(d-\Delta) = \frac{2k\ \delta T}{P} \tag{9}$$

where k is the thermal conductivity, P the power density, and δT the temperature difference across the crust.

If the melting point is again 2700 K and the surface temperature 600 K (δT = 2100 K), as done in Section 4.1, substituting the numerical values

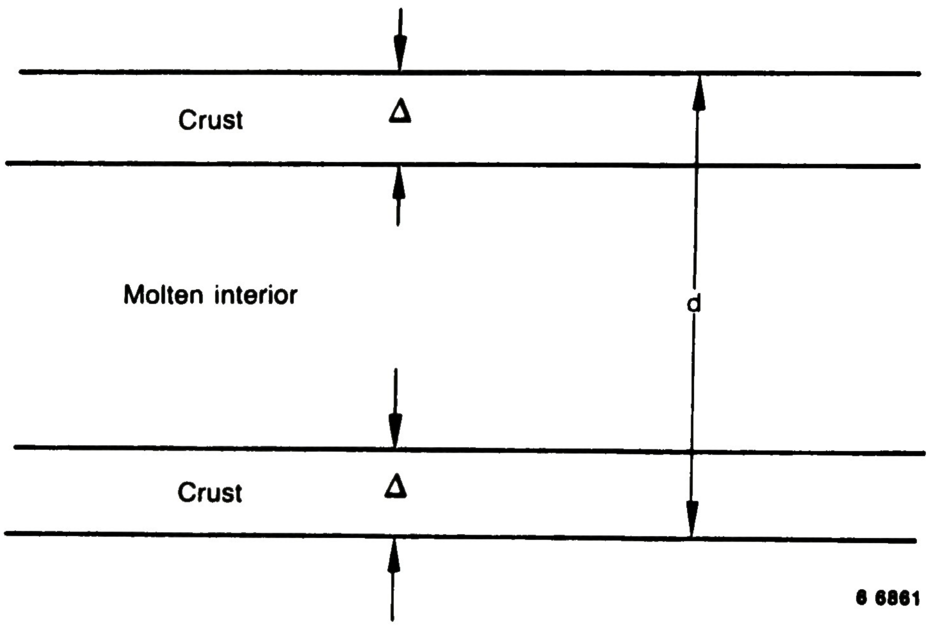

Figure 3. Debris bed with molten interior.

of the κ's and ρ's for solid mixtures given in Section 3 and the power density, P, by Equation 2, Equation 9 becomes, numerically,

$$\Delta(d-\Delta) = \frac{38.67 - 37.62\ f}{f} \cdot \frac{M_o}{P_o} \tag{10}$$

where d and Δ are in m, M_o in kg, and P_o in W; f is the mass fraction of uranium dioxide in the mixture.

Tables 6 and 7 give the equilibrium crust thicknesses calculated from Equation 10, assuming 93,100 kg for M_o and the decay power P_o given in Table 1. The fuel mass fraction, f, is assumed to be 0.5 and 0.9 respectively in Tables 6 and 7. The release fraction of the more volatile fission products is assumed to be 0.5 in both cases. A fuel mass fraction equal to 0.5 generally represents debris material with unoxidized fuel rods embedded in relocated zircaloy and the fuel previously liquefied by zircaloy at temperatures below 2500 K. A fuel mass fraction equal to 0.9 more closely represents material of compacted fuel pellets and highly oxidized zircaloy cladding.

Tables 6 and 7 indicate considerable variation in the crust thickness as the composition of the debris bed changes. If all of the zircaloy in the TMI-2 core and 50% of its fuel collapsed to form a solid debris bed, the mass fraction of uranium dioxide in the debris bed would be about 0.5 and the debris bed thickness would be approximately 0.8 m. Table 6 shows this debris bed without a molten interior under equilibrium conditions if the power density compares to that from decay heat 3 h after shutdown and if 50% of the more volatile fission products is released. On the other extreme, a debris bed 2 m thick, composed of 90% fuel by mass, would have a solid crust less than 0.02 m thick if the power were comparable to that from decay heat 10 h after shutdown with 50% of the more volatile fission products released. The TMI-2 debris bed, formed during the accident before the melt relocation to the lower plenum (about 3 h, 46 min after the beginning of the accident), would be somewhere between these two extremes.

TABLE 6. EQUILIBRIUM CRUST THICKNESS, Δ, IN METERS, FOR VOLATILE FISSION PRODUCTS RELEASE FRACTION EQUAL TO 0.5 AND FUEL MASS FRACTION, f, EQUAL TO 0.5

Time (h)	Debris Bed Thickness, a, in meters						
	0.80	1.00	1.20	1.40	1.60	1.80	2.00
1	0.20	0.14	0.11	0.092	0.079	0.069	0.062
2	0.32	0.19	0.14	0.12	0.10	0.081	0.080
3	--[a]	0.22	0.17	0.14	0.12	0.10	0.090
4	--	0.25	0.19	0.15	0.13	0.11	0.099
5	--	0.28	0.20	0.16	0.14	0.12	0.11
10	--	0.49	0.27	0.21	0.18	0.15	0.13
24	--	--	0.41	0.29	0.24	0.20	0.18

a. No molten interior.

TABLE 7. EQUILIBRIUM CRUST THICKNESS, Δ, IN METERS, FOR VOLATILE FISSION PRODUCT RELEASE FRACTION EQUAL TO 0.5 AND FUEL MASS FRACTION, f, EQUAL TO 0.9

Time (h)	Debris Bed Thickness, d, in meters								
	0.40	0.60	0.80	1.00	1.20	1.40	1.60	1.80	2.00
1	0.046	0.028	0.021	0.016	0.014	0.012	0.010	0.0090	0.0081
2	0.061	0.037	0.027	0.021	0.017	0.015	0.013	0.012	0.010
3	0.071	0.042	0.030	0.024	0.020	0.017	0.015	0.013	0.012
4	0.079	0.046	0.033	0.026	0.022	0.018	0.016	0.014	0.013
5	0.088	0.050	0.036	0.028	0.023	0.020	0.017	0.015	0.014
10	0.12	0.063	0.045	0.035	0.029	0.024	0.021	0.019	0.017
24	--[a]	0.085	0.059	0.046	0.038	0.032	0.028	0.025	0.022

a. No molten interior.

5. TRANSIENT HEATUP OF THE TMI-2 DEBRIS BED

This section presents a transient calculation of the TMI-2 debris bed heatup. The calculation assumes: (a) the debris bed was formed after a reactor coolant pump was turned on momentarily at about 2 h, 54 min (174 min) into the accident; (b) the bed consisted of loose debris in the upper region and a cohesive mass in the lower; (c) the mass in the lower region consisted of relocated zircaloy, zirconium dioxide, and liquefied fuel with embedded fuel rod stubs; (d) the cohesive mass was divided into two zones of different composition--the lower metallic in character and the upper ceramic; (e) the rubble on top of the cohesive mass was continuous; and (f) heat was transferred from the interior to the surface by conduction alone. The calculation is carried to 50 min after the reactor coolant pump transient so the results of the thermal calculation may represent the state of the debris bed just before the hypothesized melt relocation to the lower plenum occurred (about 3 h, 46 min [226 min] into the accident).

5.1 Debris Bed Configuration

The one-dimensional model of the TMI-2 debris bed, constructed in this section, assumes that the debris bed was formed shortly after the reactor coolant pump transient (about 174 min into the accident) and maintained its configuration until melt relocation to the lower plenum (about 226 min into the accident).

During the early phase of the accident, the upper part of the reactor core would have oxidized rapidly; the zircaloy cladding would have melted, relocated with some liquefied fuel to the lower part of the core, and congealed between the fuel rods to form a solid mass. Some highly oxidized cladding and fuel pellets would have remained in the upper part of the core. During the reactor coolant pump transient about 174 minutes into the accident, water was pumped through the core causing the oxidized cladding and fuel pellets to shatter and collapse into a pile of rubble on top of the solid crust. This formed the upper part of the debris bed.

The method of constructing the debris bed model, based, in part, on mass balance, considers only the fuel rods in the active fuel region. It ignores the other rods, including the control, burnable poison, and instrument rods as well as structural materials, such as grid spacers. The active fuel rods were originally 3.66 m high and had a total uranium dioxide mass of 93,100 kg and a zircaloy mass of 20,100 kg. The material originally occupying the 1.31 m-high upper void region presumably relocated either to the solid region or to the rubble bed. Debris bed probing data[8] show an average rubble depth of 0.80 m. Samples from the rubble bed indicate a bulk density of about 4400 kg/m^3 and a uranium-to-zircaloy mass ratio of about 7. These figures represent an approximate 40% zircaloy depletion from an undamaged fuel rod.[9] A simple mass balance calculation shows that 53% of the original uranium dioxide and 73% of the original zircaloy in the top 2.11 m of the core would have relocated to the lower regions of the core, given the following assumptions: (a) the rubble was a uranium dioxide and zirconium dioxide mixture, (b) damage was uniform across the core, and (c) the debris bed included the partially damaged peripheral assemblies.

The relocated material from the upper part of the core presumably filled the free space between the fuel rods under the rubble bed. According to preliminary posttest examinations this is what happened to the fuel bundles used in the Severe Fuel Damage experiments performed in the Power Burst Facility.[10,11,12,13] When peak temperatures during these experiments exceeded 2400 K, the relocated material in each bundle formed a solid mass near the bottom of the bundle where the temperature was comparatively low. The relocated material composition appears to vary from mostly zircaloy to a U-Zr-O ceramic. So it may be assumed of the TMI-2 debris bed that one half of the relocated zircaloy and uranium dioxide resided in the lower part of the solid bed, and the other half in the upper part. Moreover, the relocated zircaloy in the upper part of the solid bed was oxidized to zirconium dioxide, causing the resulting solid to behave like a U-Zr-O ceramic. The original fuel rod stubs embedded in the relocated material were presumably unaffected by oxidation. Thus, calculations based on the densities of uranium dioxide, zircaloy, and zirconium dioxide show the material relocated below the rubble would extend to 0.61 m above the bottom of the active core.

If there were uniform damage across the TMI-2 core (cross-section area, 8.3 m^2), its configuration after forming the rubble bed can be divided into five regions. These are, sequentially from the bottom of the core:

1. Fuel rod stubs at the lower end of the core, 0.61 m high, consisting of 3,350 kg of zircaloy and 15,500 kg of uranium dioxide

2. A fused mass, metallic in character, 0.44 m high, consisting of 6,600 kg of zircaloy and 25,500 kg of uranium dioxide

3. A fused mass, ceramic in character, 0.50 m high, consisting of 2,800 kg of zircaloy, 5,700 kg of zirconium dioxide, and 27,100 kg of uranium dioxide

4. A rubble bed, 0.80 m high, consisting of 4,300 kg of zirconium dioxide and 25,000 kg of uranium dioxide

5. A void region, 1.31 m high, at the upper end of the core.

The debris bed in the transient heatup calculations comprises Regions 2, 3 and 4.

5.2 Debris Bed Thermal Properties

Individual thermal conductivities of Regions 2, 3, and 4, defined in Section 5.1, are taken to be the volume-weighted average of the thermal conductivities of the constituents. Equation 1 in Section 3 gives the formula used. Section 3 also gives in the numerical values. The volumetric heat capacity in each region equals the average density in that region times a constant specific heat of 500 J/kg-K, (see Section 3). The calculations add the heat of fusion to the heat capacity in a temperature interval within which the material would presumably melt. The calculation assumes the heat of fusion is distributed evenly in that temperature interval. It assumes the metallic zone (Region 2) melts from 2150 to 2250 K; the ceramic zone (Region 3), 2750 to 2850 K; and the rubble zone (Region 4), 2750 to 2900 K. For the metallic melt, this amounts to 23 MJ/m^3-K; for the ceramic melt, 30 MJ/m^3-K; and for the rubble bed, 10 MJ/m^3-K. The conductivities and the volumetric heat capacities in each region are given in Table 8. The volumetric heat capacities listed do not include the heat of fusion.

The power density in each region of the debris bed is calculated from its uranium dioxide content. These calculations assume (a) the relocated fuel in Regions 2 and 3, and the fuel in the rubble bed released 50% of their more volatile fission products; and (b) the original fuel in Regions 2 and 3 did not release volatile fission products. Calculations of the average decay power per unit mass of uranium dioxide are taken from the total core decay power given in Table 1 and the core uranium dioxide mass of 93,100 kg. Calculations based on the above assumptions show the relative power densities in the three regions stayed fairly constant from 3 to 5 h after reactor shutdown. The relative power densities are: 0.41 for the metallic zone (Region 2), 0.38 for the ceramic zone (Region 3), and 0.21 for the rubble zone (Region 4). The total power in the debris bed is 18.6 MW at three hours and 17.0 MW at 4 h after reactor shutdown. The total power between 3 and 4 h is linearly interpolated from these two values.

5.3 Transient Thermal Conduction

The equation of transient thermal conduction in one-dimensional slab geometry may be written as

$$C\frac{\partial T}{\partial t} = P + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) \qquad (11)$$

where C is the heat capacity per unit volume, T the temperature, P the power density (power per unit volume), k the thermal conductivity, z the spatial variable, and t the time variable. Section 5.2 gives the thermal properties of the TMI-2 debris bed model.

TABLE 8. HYPOTHESIZED TMI-2 DEBRIS BED THERMAL PROPERTIES

	Thermal Conductivity (W/m-K)	Volumetric Heat Capacity (MJ/m^3-K)
Metallic zone	18.7	4.4
Ceramic zone	8.2	4.3
Rubble bed	2.3	2.2

Based on a recent calculation using the SCDAP code,[14] the temperature in the relocated cohesive mass, just before the reactor coolant pump transient approximately 174 min into the accident, ranged from 1000 K at its lower surface to about 2200 K at its top surface. After the pump transient, the rubble bed could have cooled to about 1500 K; the lower surface of the cohesive mass cooled to about 800 K, while the interior of the mass remained at high temperatures. The transient calculation uses these assumed temperatures to define the initial temperature distribution.

The boundary conditions for the transient calculation are: (a) the lower surface of the debris bed radiates to a volume whose heat capacity is equivalent to about 8000 kg of steel; and (b) the upper surface radiates to a volume whose heat capacity is equivalent to 12,000 kg of steel. The upper heat sink may be considered as the affected structural material in the upper plenum, and the lower heat sink may be considered as the fuel rods stubs below 0.61 m (Region 1) and the structural material in the lower plenum. Both upper and lower surfaces are assumed to have an emissivity of 0.8.

Figure 4 shows the model of the TMI-2 debris bed along with the initial and boundary conditions for the transient calculation.

The heat transfer features of the RELAP5/MOD2 code,[15] with an update to simulate radiating surfaces, are used to carry out the numerical integration of Equation 11 for the TMI-2 debris bed model.

5.4 Debris Bed Heatup Results

Figure 5 shows the results of the transient calculation. The metallic zone spans from 0.61 m to 1.05 m as measured from the bottom of the active fuel; the ceramic zone, from 1.05 to 1.55 m; and the rubble zone, from 1.55 to 2.35 m. The temperatures at both ends of the debris bed represent the sink temperatures in the lower and upper plenums respectively.

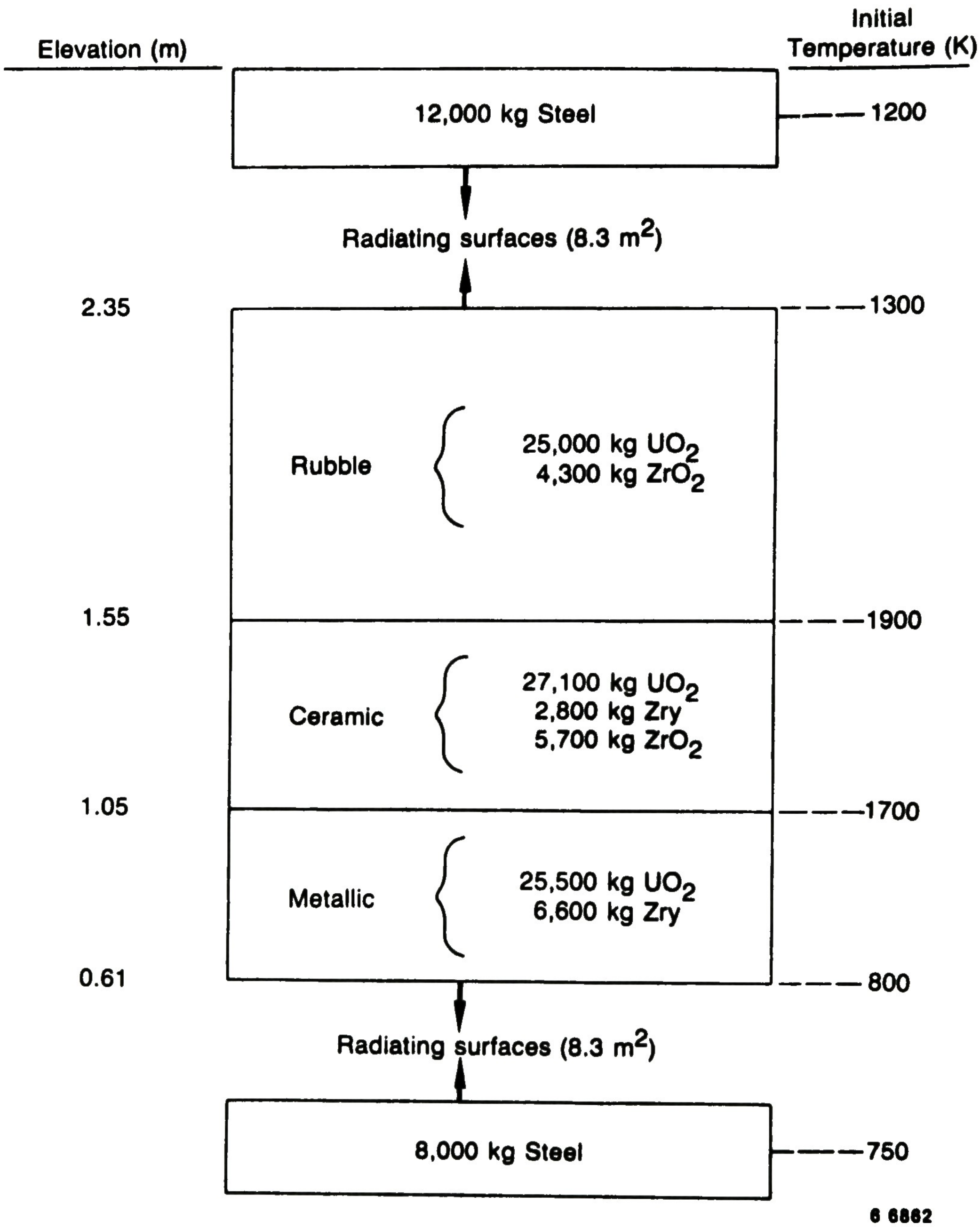

Figure 4. TMI-2 core debris bed model.

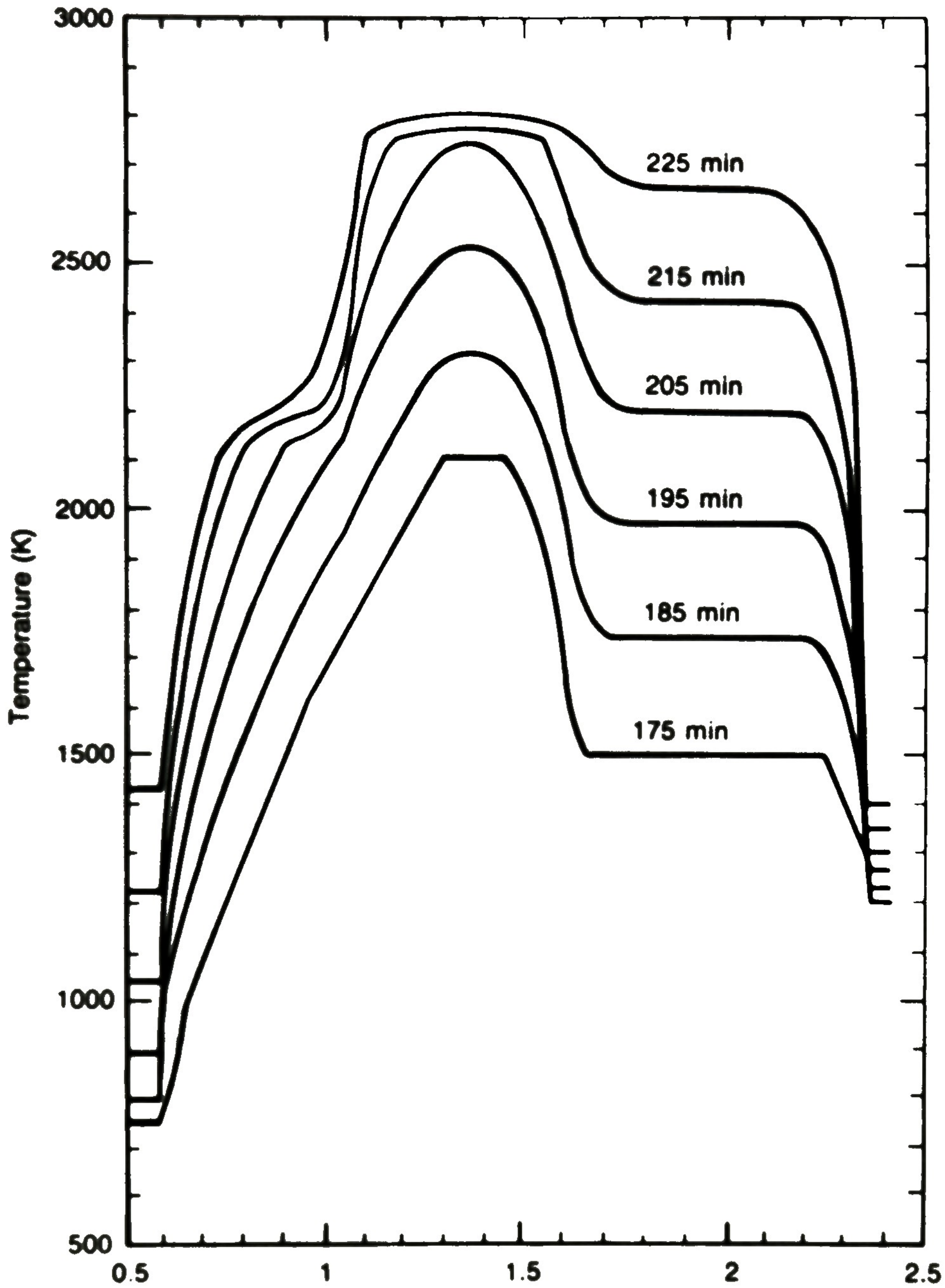

Figure 5. Calculated TMI-2 debris heatup after 175 min.

The calculation starts from the curve in Figure 5 labeled 175 min and ends at the curve labeled 225 min. At 225 min, the temperature of the lower heat sink was slightly above 1400 K. The metallic zone had a lower crust about 0.17 m thick. Above the crust there was a melting zone about 0.18 m thick with 40% molten material. The remaining 0.09 m of the metallic zone was completely molten. The ceramic zone had a lower crust about 0.08 m thick with 40% of the ceramic on top of the crust molten. The rubble bed on top of the ceramic zone remained solid, and the upper heat sink temperature was about 1400 K. The total molten material in the debris bed at 225 min was about 23,800 kg, 18,500 kg of which was uranium dioxide. Figure 6 illustrates the condition of the debris bed at 225 min, as modeled here. Please note that the model applies to a uniformly damaged core and that the damage includes the peripheral assemblies, which, we know were not part of the TMI-2 debris bed.

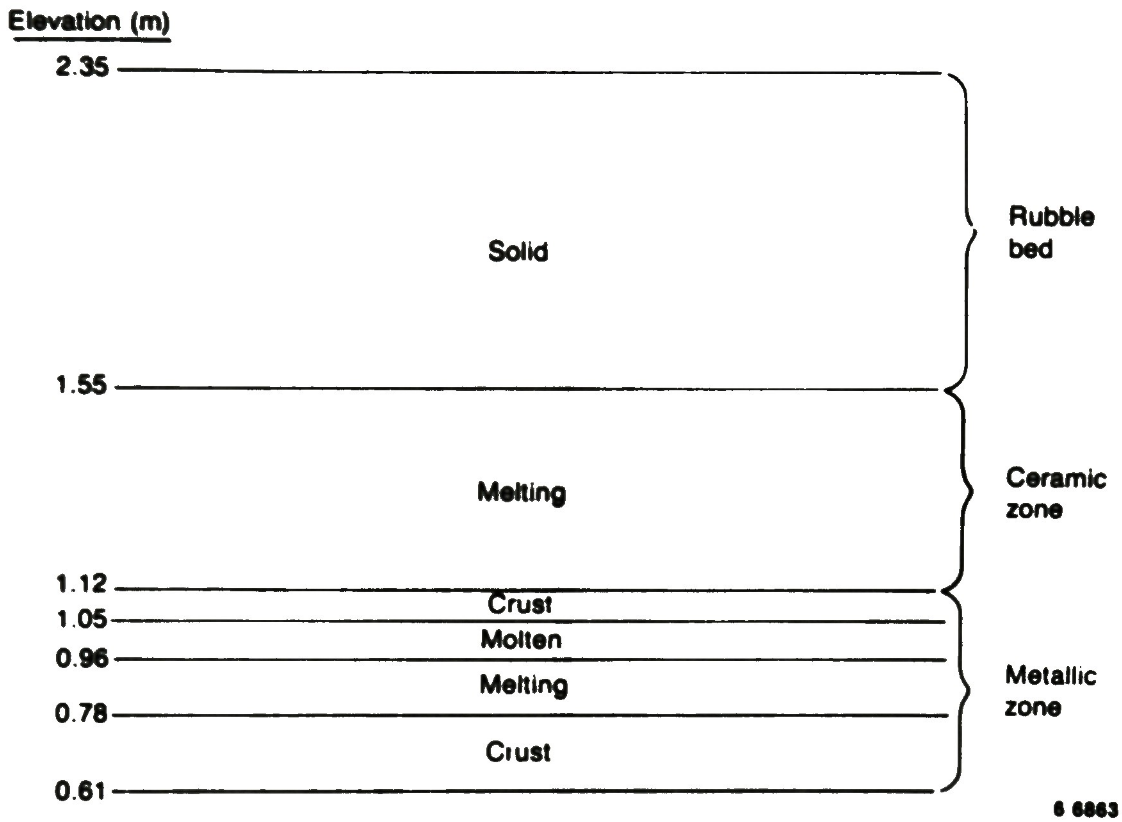

Figure 6. Calculated TMI-2 debris bed conditions at 225 min into the accident; bottom of the fuel stack is at zero elevation.

6. SUMMARY AND DISCUSSION

The calculations of the TMI-2 core decay heat levels were based on a simplified operating history of 100 days near full power at 2670 MW. These calculations are for the time period between 1 and 24 h after the reactor scram. During the accident, some of the fuel must have gone through a high-temperature phase before a debris bed formed in the TMI-2 core. This high temperature phase would have caused a fraction of the more volatile fission products (noble gases, cesium, iodine, and tellurium) to be released. Consequently, for the study of debris bed thermal behavior, the decay heat was calculated as a function of the release fraction of these fission products. The calculated core decay heat varied from 36 MW at 1 h after scram with no release of fission products to 10 MW at 24 h after scram with a total release of the more volatile fission products.

The composition of the debris bed was a crucial parameter in the thermal calculations. Both the power density and the thermal conductivity can vary considerably according to whether or not the debris bed content was mainly uranium dioxide fuel or zircaloy. Simple expressions were deduced for the power density and the thermal conductivity of a mixture of uranium dioxide and zircaloy. These deductions were deemed suitable for use in one-dimensional, slab-geometry calculations. Experiments must confirm whether or not these deductions of the thermal conductivity are applicable.

The equilibrium thickness of a debris bed with a molten interior was determined as a function of both the fuel's mass fraction and of the more volatile fission products' release fraction. Given the decay heat levels as determined for the first day after reactor scram, the minimum thickness can vary over a wide range from 0.1 to 1.8 m. The lower limit applies to a debris bed composed of 90% fuel at 1 hour after scram with only 10% release of the more volatile fission products; the upper limit to a debris bed composed of 30% fuel at 24 h after scram with 90% release of the more volatile fission products.

The equilibrium crust thickness of a debris bed with a molten interior was calculated as a function of the total thickness of the debris bed for fuel mass fractions at 0.5 and 0.9 respectively. A debris bed with a fuel mass fraction of 0.5 would be more representative of one formed from relocated zircaloy and undamaged fuel rod stubs; while one with a fuel mass fraction at 0.9 would be more representative of a debris bed composed of fuel pellets and highly oxidized cladding remaining after most of the zircaloy had melted and flowed away. The equilibrium crust thickness was calculated as only 0.01 m for a debris bed 2 m thick with the higher fuel content. The equilibrium crust thickness for one with the lower fuel content would be about 0.1 m a few hours after reactor scram. In both cases, these calculations assume that 50% of the more volatile fission products was released.

Based on the TMI-2 debris bed post-accident examinations and on some assumptions about the relocation of zircaloy and liquefied fuel during the rapid oxidation phase of the accident, a model of the TMI-2 debris bed was constructed for a transient thermal calculation during the time period between 175 and 225 min after the accident began. The overall thickness of the debris bed in one-dimensional slab geometry was about 1.8 m. Given the decay heat level in the debris bed, its thickness was well within the limits of those for debris beds with molten interiors and under thermal equilibrium. The transient calculation indeed showed that by 225 min a significant fraction of interior of the debris bed was molten. Assuming the damage was uniform across the core, the molten material amounted to about 24,000 kg, 18,000 kg of which was uranium dioxide. Because of the following two factors, the actual amount of molten material would be about half the quoted amount, or 12,000 kg total, 9000 kg uranium dioxide. First, the debris bed did not actually extend to the peripheral assemblies in the core. Second, there would have been a solid crust near the radial edge of the debris bed. The crust thickness at the lower end of the debris bed was calculated as about 0.17 m at 225 min. The rubble above the solid bed was not predicted to melt after being partially cooled by water pumped through the core at about 174 min.

The equilibrium calculations were fairly straightforward. The formulas deduced for the minimum thickness of a debris bed with a molten interior and for the crust thickness of a debris bed with a molten interior were quite simple in one-dimensional slab geometry. The main uncertainty in the results would come from uncertainties in the thermal conductivities of the material comprising the debris bed.

The transient calculation of the heatup of the TMI-2 debris bed showed molten material in the debris bed at 225 min into the accident. But, it also showed a crust at the lower surface. Therefore, this calculation alone does not indicate that molten material relocated into the lower plenum at that time. However, two scenarios may be constructed to show how the lower crust could have failed. First the temperature at the lower surface of the debris bed was calculated to be about 1500 K at 225 min. If the lower surface was indeed rich in zircaloy and if there was sufficient steam flow along the lower surface, rapid oxidation of the surface would take place, thus providing an additional heat source. This additional heat could possibly have increased the temperature of the lower surface above its melting point and have created a hole for the molten material in the interior of the debris bed to flow out. Second, there could have been a mechanical failure due to excess stress on the lower surface. The expansion of the molten material inside the debris bed could have produced this stress.

The transient calculation is limited in several aspects. In addition to the uncertainties about the thermal properties of the debris bed and the assumption of one-dimensionality, there are uncertainties in the initial temperature distribution and in the assumption that steam or liquid water cooling was absent, especially from the rubble bed region. However, these uncertainties do not invalidate the conclusion that the debris bed interior would melt. The sheer size of the debris bed (1.8 m thick), seen from the results of the equilibrium calculations, reenforces the conclusion. Of course, the time the crust failed and allowed molten material to relocate would depend both on the debris bed thermal properties as well as its geometry.

Defueling the TMI-2 core is underway. The geometrical configuration of the core will be noted at every level as the defueling proceeds. Also, there are plans to obtain core samples at different elevations in the debris bed. These samples will be examined to obtain information on their physical and chemical properties and their radioisotopic content. These additional pieces of information on the damaged TMI-2 core will undoubtedly greatly enhance our understanding of the thermal behavior of the degraded core.

7. REFERENCES

1. J. G. Kemeny, et al., Report of the President's Commission on the Accident at Three Mile Island, October 30, 1979.

2. M. Rogovin and G. T. Frampton, Three Mile Island: A Report to the Commissioners and to the Public, NUREG/CR-1250, January 1980.

3. Nuclear Safety Analysis Center, Analysis of Three Mile Island Unit 2 Accident, NSAC-80-1, NSAC-1 Revised, March 1980.

4. D. W. Akers ltr to J. M. Broughton, "TMI-2 Core Nodular ORIGEN2 Calculations," DWA-18-85, EG&G Idaho, Inc., April 17, 1985.

5. A. G. Croff, ORIGEN2--A Revised and Updated Version of the Oak Ridge Isotope Generation and Depletion Code, ORNL-5621, July 1980.

6. United States Nuclear Regulatory Commission, Technical Bases for Estimating Fission Product Behavior during LWR Accidents, NUREG-0772, 1981.

7. D. L. Hagrman, Materials Properties Models for Severe Core Damage Analysis, EGG-CDD-5801, May 1982.

8. V. R. Fricke, "Core Debris Bed Probing," TMI-2 Technical Planning Bulletin, TPB-84-8, December 21, 1984.

9. D. W. Akers et al., Draft Report: TMI-2 Core Debris Grab Samples--Examination and Analysis, EGG-TMI-6853, July 1985.

10. R. K. McCardell et al., Severe Fuel Damage Test Series, Severe Fuel Damage Scoping Test Quick Look Report, EG&G Idaho, Inc., December 1982.

11. R. K. McCardell et al., Severe Fuel Damage Test 1-1 Quick Look Report, EG&G Idaho, Inc., October 1983.

12. R. W. Miller et al., Severe Fuel Damage Test 1-3 Quick Look Report, EG&G Idaho, Inc., October 1984.

13. R. W. Miller et al., Severe Fuel Damage Test 1-4 Quick Look Report, EG&G Idaho, Inc., July 1985.

14. C. M. Allison ltr to J. M. Broughton, Estimate of TMI-2 Core Damage at 174 minutes, CMA-11-85, EG&G Idaho, Inc. August 15, 1985.

15. V. H. Ransom and R. J. Wagner, RELAP5/MOD2 Code Manual, EGG-SAAM-6377, April 1984.